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Horizontal branch stars and the neutrino signal from SN1987a

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ABSTRACT

The observed lifetimes of horizontal branch stars yield an upper bound of $3\times10^{-50}\,\mathrm{cm}^2$ for the process $\gamma+{}^4\mathrm{He}\to{}^4\mathrm{He}+X^\circ$ involving some hypothetical boson X°. This result excludes a recent interpretation of the angular distribution of the IMB and Kamioka signals of the supernova 1987a in terms of the coherent scattering process $X^\circ+{}^{16}\mathrm{O}\to{}^{16}\mathrm{O}+\gamma$.

The signal of the supernova 1987a in the IMB[1] and Kamioka[2] underground detectors has generally been interpreted as being due to the inverse beta reaction $\overline{\nu}_e+p\to n+e^+$ and, perhaps, one event in Kamioka due to the elastic scattering process $\nu_e+e^-\to e^-+\nu_e$. The former process yields an essentially isotropic distribution of the final state e^+. The observed angular distribution, however, shows a forward bias which must be explained, in the neutrino interpretation of the signal, as a statistical fluctuation. The probability for such a fluctuation is on the order of 1%. In a recent paper, van der Velde has suggested[3] that the signal could be interpreted, instead, as a coherent scattering process $X^\circ+{}^{16}\mathrm{O}\to{}^{16}\mathrm{O}+\gamma$ of some hypothetical boson X° with mass $m_x\lesssim20\,\mathrm{eV}$. The forward bias is achieved by the relevant form factor $e^{-q^2R^2}$ where q

is the energy momentum transfer of the reaction, and R is some characteristic radius of the oxygen nucleus. The required cross section per nucleon is $\sigma_x \approx 1.6\times10^{-44}\,\mathrm{cm}^2$. Then the observed SN1987a signal could be taken as evidence for such X° particles.

However, the process envisioned by van der Velde occurs, in the reverse direction, in the interior of stars. In helium burning red giants (horizontal branch stars) the reaction $\gamma + {}^4\mathrm{He} \to {}^4\mathrm{He} + X^\circ$ produces a large flux of X° particles, leading to an "exotic" energy loss mechanism and therefore to an acceleration of the HB evolutionary phase. Observations of the number of HB stars in stellar clusters require this exotic energy loss rate to be less than about[4,5] $100\,\mathrm{erg\,g^{-1}\,s^{-1}}$ in the core of these stars where the temperature is $1\times10^8\,\mathrm{K}$, the density is $1\times10^4\,\mathrm{g\,cm^{-3}}$, and the initial composition is mainly helium, with carbon and oxygen building up in the process of burning. Therefore we find that the photo production cross section of X° on ${}^4\mathrm{He}$ is constrained by $3\times10^{-50}\,\mathrm{cm}^2$. Assuming coherence as in Ref. 3 we have to divide by 16 to obtain the bound $\sigma_x \lesssim 1.8\times10^{-51}\,\mathrm{cm}^2$ for the cross section per nucleon.

Our result applies to $E_x = \mathcal{O}(10\,\mathrm{keV})$ while the X° particles from the supernova have $E_x = \mathcal{O}(10\,\mathrm{MeV})$. Hence $\sigma_x(10\,\mathrm{MeV})/\sigma_x(10\,\mathrm{keV}) \gtrsim 10^7$ and van der Velde's scenario requires that σ_x strongly increases with E_x. Even a scaling with E_x^2 would be unacceptable or, at best, marginally acceptable. If X° is some scalar or vector particle which couples to nucleons with a fine structure constant α_x, the Thomson photo production cross section on nucleons is about $\alpha_x\alpha/m_N^2$ with no energy dependence. Also, the Primakoff effect with the exchange of a virtual photon has only a weak energy dependence from the Coulomb logarithm[6]. If one introduces higher derivative couplings, one can achieve a cross section that varies with an appropriate power of E_x, or rather, with some power of q^2 which introduces a *backward* bias of the cross section. Therefore it does not seem possible to retain the simple $e^{-q^2R^2}$ form factor *and* to obtain the required energy dependence. Hence we believe that van der Velde's interpretation of the angular distribution of the IMB and Kamioka signals is inconsistent with astronomical data on the lifetimes of HB stars.

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